System Integration of Distributed Power for Complete Building Systems

Subcontract Number: NAD-0-30605-10

NAD-0-30605-10

Principal Investigator: Dr. Robert Kramer

NREL Technical Monitor: Holly Thomas

Electric Distribution Transformation Program

2004 Annual Program and Peer Review Meeting,
October 28-30, 2003, Coronado (San Diego), California

Relevance to Problems & Needs

- The objective of this subcontract over its planned 3-year duration is to advance distributed power technology.
- The specific objective of work under this subcontract is to identify the system integration and implementation issues for distributed generation, and to develop and test potential solutions to these issues

Task Overview & Relevance

Task #	Description	Project Year	Relevance*
1	**DG interconnection issues**	**1**	**6,20**
2	**Zoning and Permitting issues for DG**	**1**	**11,12**
3	**DG system integration and performance considerations**	**1**	**6,7,15**
4	**CHP System Design**	**2**	**4,15,28**
5	**DG interconnection development**	**2**	**6,7**
6	**CHP performance and interactions issues**	**2**	**15,23**
6A	**DG interconnection demonstration**	**2**	**7**
7	**CHP system design recommendations**	**3**	**4,21,23**
8	**DG interconnection structure**	**3**	**6,7**
9	**CHP system integration and performance recommendations**	**3**	**15,17,23**
10	**Controllable inverter model for DG**	**3**	**15,28**
11	**Economic benefit of DG to electric distribution grid**	**3**	**5,6,8,11,21**
12	**Electric transfer switching design issues**	**3**	**20,26**
13	**Explore research agenda for next generation electric distribution system**	**3**	**11,24**
14	**Consideration of the interaction of multiple DG units on the distribution network**	**3**	**6,7**

*** Page number of DOE's National Electric Vision Document (Final version, July 31, 2003)**

Deliverables (Option Year II)

D-3.1	Monthly Letter Progress Report
D-3.2	Draft Final Summary Subcontract Report
D-3.3	Final Summary Report
D-3.4	Preliminary assessment report for DG integration and aggregated systems testing. (Task 9)
D-3.5	Report describing prototype recommendation for incorporating CHP systems into building designs.(Task 7)
D-3.6	Deliver report regarding the technical, institutional and regulatory issues relating to DG power. (Task 8)
D-3.7	Deliver initial documentation of modeled generic inverter. (Task 10)
D-3.8	Deliver documentation of modeled controllable inverter design & initial model testing results.(Task 10)
D-3.9	Deliver final report detailing the design and results for controllable inverter (Task 10)
D-3.10	Deliver invoice for computer
D-3.11	Deliver documentation for the inverter model. (Task 11)
D-3.12	Deliver report of initial DG distribution system economic model test results. (Task 11)
D-3.13	Report documenting model, effect, and value of DG to distribution system (Task 11)
D-3.14	Report with a listing of the currently available transfer switching devices, with expected effects (Task 12)
D-3.15	Tabulation of the defined issues influencing transfer switch operation. (Task 12)
D-3.16	Report defining the issues influencing transfer switch operation (Task 12)
D-3.17	Deliver agenda, participant list and meeting presentation materials. (Task 13)
D-3.18	Deliver report summarizing meeting conclusions. (Task 13)
D-3.19	Deliver interim report describing the Chesterton model. (Task 14)
D-3.20	Deliver final report summarizing work conducted in Task 14. (Task 14)

Technical Challenges of Current Practices

- At the start of the project there were many unanswered questions regarding the operation, design, and interconnection of CHP systems.
  - This project has helped to provide answers to many of these issues and thereby facilitate the implementation of CHP
- There is currently a lack of knowledge regarding the economic viability, efficiency, reliability, and need for advanced controls and designs for the integration of CHP into building systems.
  - This project has provided information, technology, procedures, and designs that can be used in the future to further meet these needs and thereby help to increase the value and viability of CHP technology

Project Objectives

- Conduct a three-phase research and development effort to advance distributed power development, deployment, and integration.
- Develop, tested, and optimized several (electric/natural gas/ renewable energy) distributed power systems.
- Develop and conduct laboratory and field tests of methodologies and controls (including command, communications, monitoring, efficiency, and energy systems).
- Completely document results. At conclusion, provided DOE with computer data base of relevant information.

Technical Approach

- During Option Year 2 the emphasis has been to conclude work regarding interconnection and code issues and concentrate CHP developmental efforts on melding CHP technology with building design and operations so as to improve overall efficiency and viability.
  - NET Testing taking place at 3 test sites
    - 2 sites located in Gary, IN
      - Small office building
      - Warehouse
    - Commercial retail business and section of electric distribution system located in Chesterton, IN
  - Subcontractor efforts taking place in Lafayette, In (Ong, Sparrow, APT); Vienna, Virginia (RDC); Atlanta, Georgia (P&D)

Task 7

- CHP System Design Recommendations
  - Results
    - Analyzed various CHP design alternatives and currently making final recommendations to optimize efficiency, effectiveness, viability, and utilization of the current and future electric distribution system.
      - Considering ways to optimize implementation of various CHP technologies. Recommendations in process.
        - Electric sources including microturbines
        - Thermal and electric energy storage
        - Absorption cooling
        - Desiccant dehumidification
        - Space and hot water heating
        - Energy Recovery Vent interface and options
      - Developing methods to Maximize the benefit and viability
      - Considering operating aspects of design alternatives
      - Developing models for evaluating influence of design alternatives on CHP viability
      - Developing and testing advanced control system using fuzzy logic based neural networks to improve overall efficiency

Task 7

System test sites in Gary and Chesterton, IN

Gary, IN Test Site 2 (Warehouse)

One of two Packaged CHP Systems at Gary, IN Site

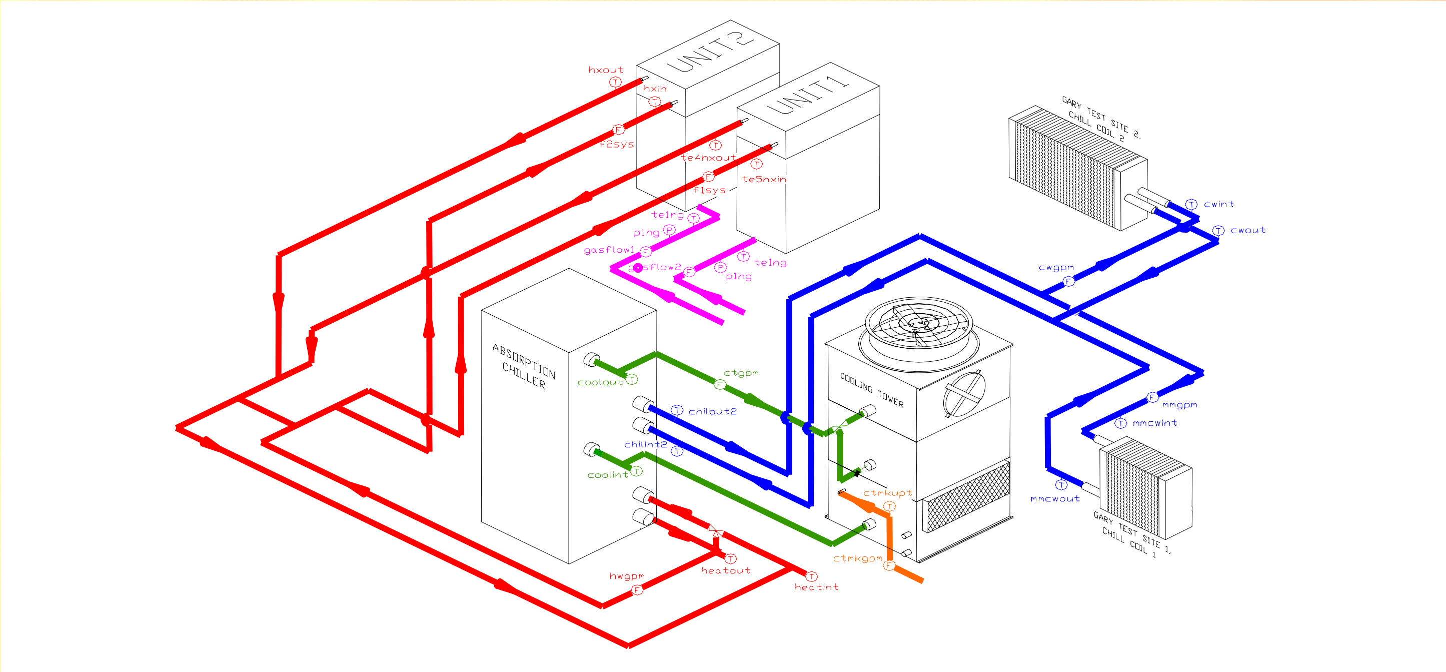
Inside CHP Packaged System

Absorption Cooling Test Unit

CHP Test System at Drug Store in Chesterton, IN

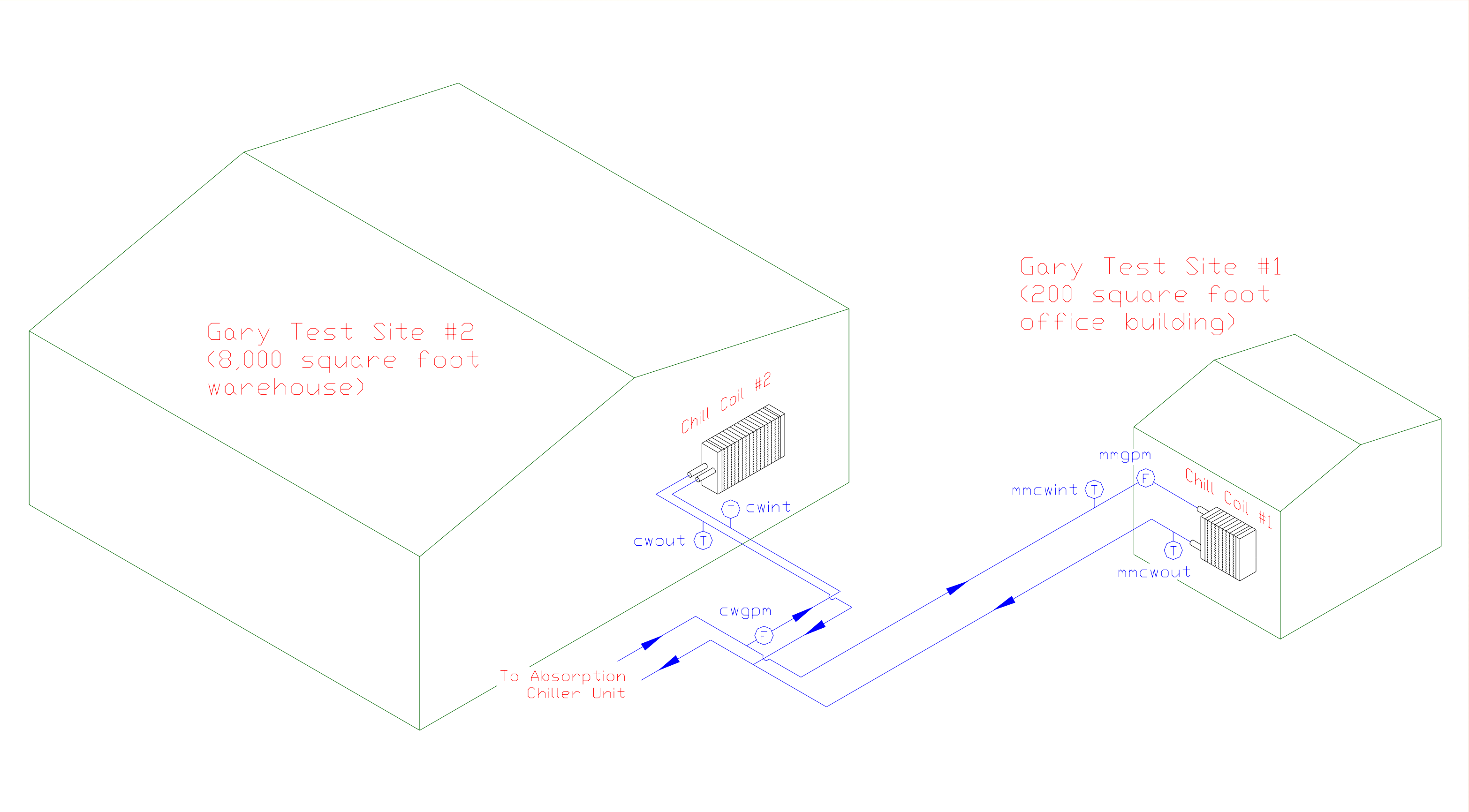
Task 7

- High efficiency is key to the viability of CHP. To obtain high efficiency heat must be used throughout the year. Absorbtion cooling is one way to use heat in warm weather and thereby improve system efficiency and the viability of CHP.
  - During warm weather, two packaged CHP systems provided heat to drive an absorption cooling system for test sites 1 and 2 in Gary, IN. A thermal and efficiency model of the system was developed to determine optimal operating conditions and design recommendations.



Task 7

- Configuration of absorption cooling test at Gary test site



Task 7

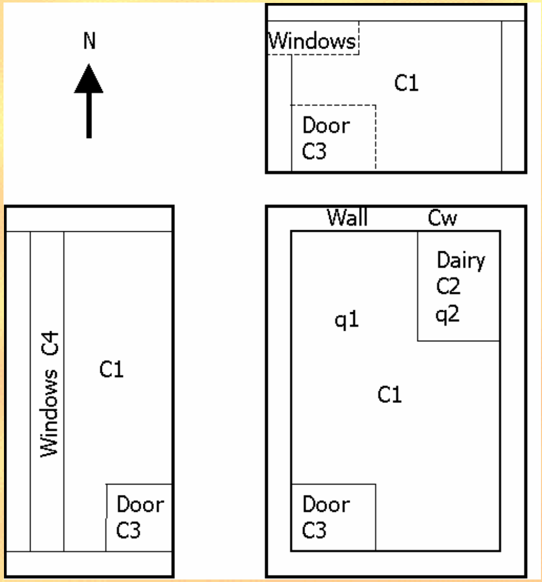
- Performance data was analyzed for various operating and design conditions for the CHP absorption system.
  - A detailed model for the automated test system was developed.

Summary of automated test results for one day

Results for 6/17/2003	Daily Average
Cooling tower efficiency	36.4 %
Heat supplied to chiller	227,081 btu/hr
Chiller refrigeration capacity	9.6 tons
Chiller coefficient of performance	0.51
Combined total fuel input	866,722 btu/hr
Combined turbine electric output	170,600 btu/hr (equivalent)
Combined turbine electrical efficiency	19.7 %
Combined overall Unit efficiency	44.1 %
Combined total heat recovered	244,079 btu/hr
Combined turbine energy lost	452,043 btu/hr
Combined Unit energy lost	484,286 btu/hr
Chill coil 2 cooling load	7.6 tons
Chill coil 1 cooling load	0.9 tons
Heat loss rate in hot fluid lines	16,998 btu/hr
Heat gain rate in chilled fluid lines	1.2 tons
Overall heating system efficiency	42.2 %
Overall chilled fluid loop C.O.P.	0.45

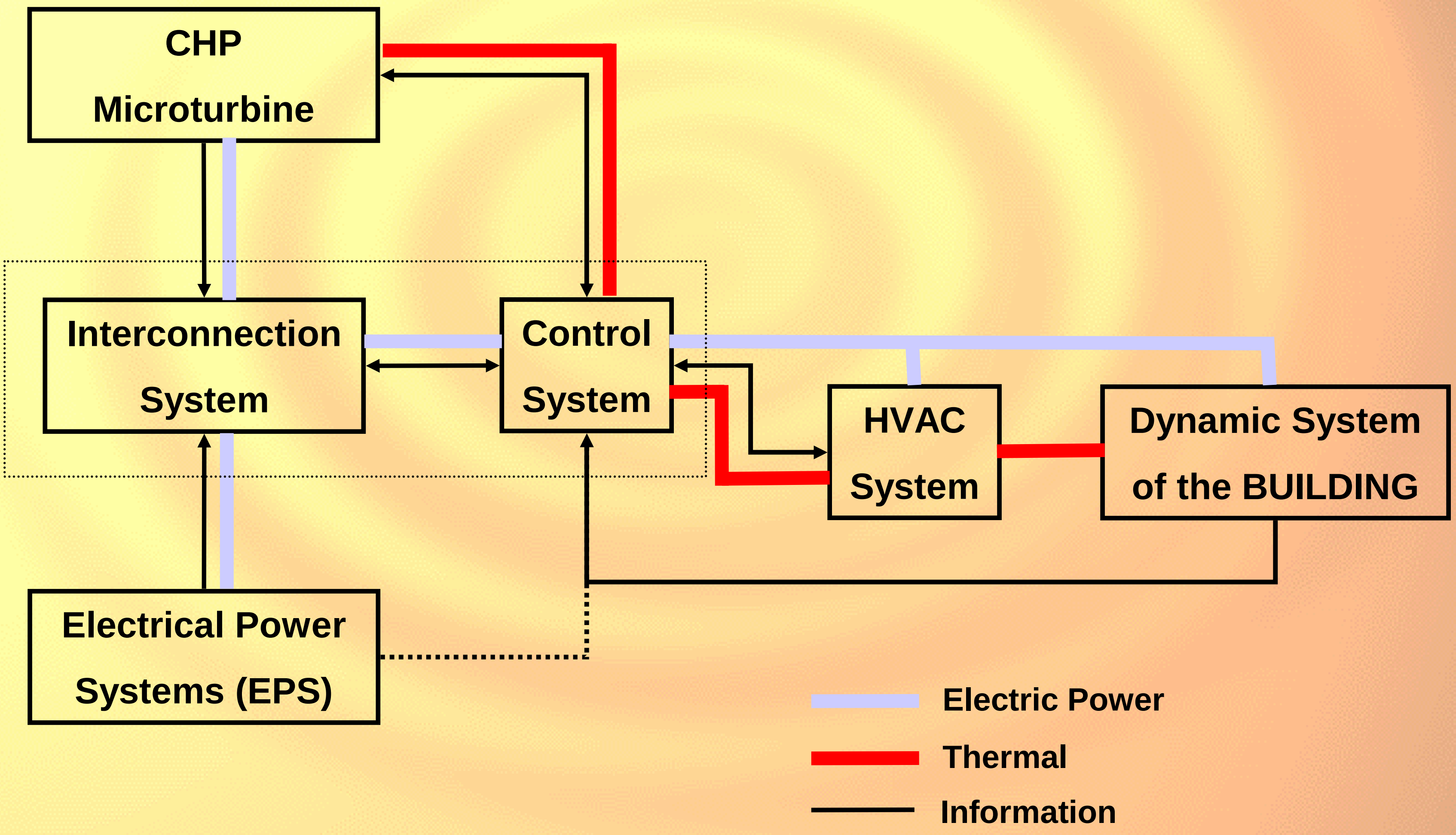
Task 7

- To improve the efficiency and consequently the viability and acceptance of CHP technology it is necessary to consider the CHP system as an integral part of the building energy system.
- An advanced adaptive control system was developed using feed forward logic and predictive control for the drug store test site in Chesterton, IN
  - Building Model Zones for Chesterton Test Site



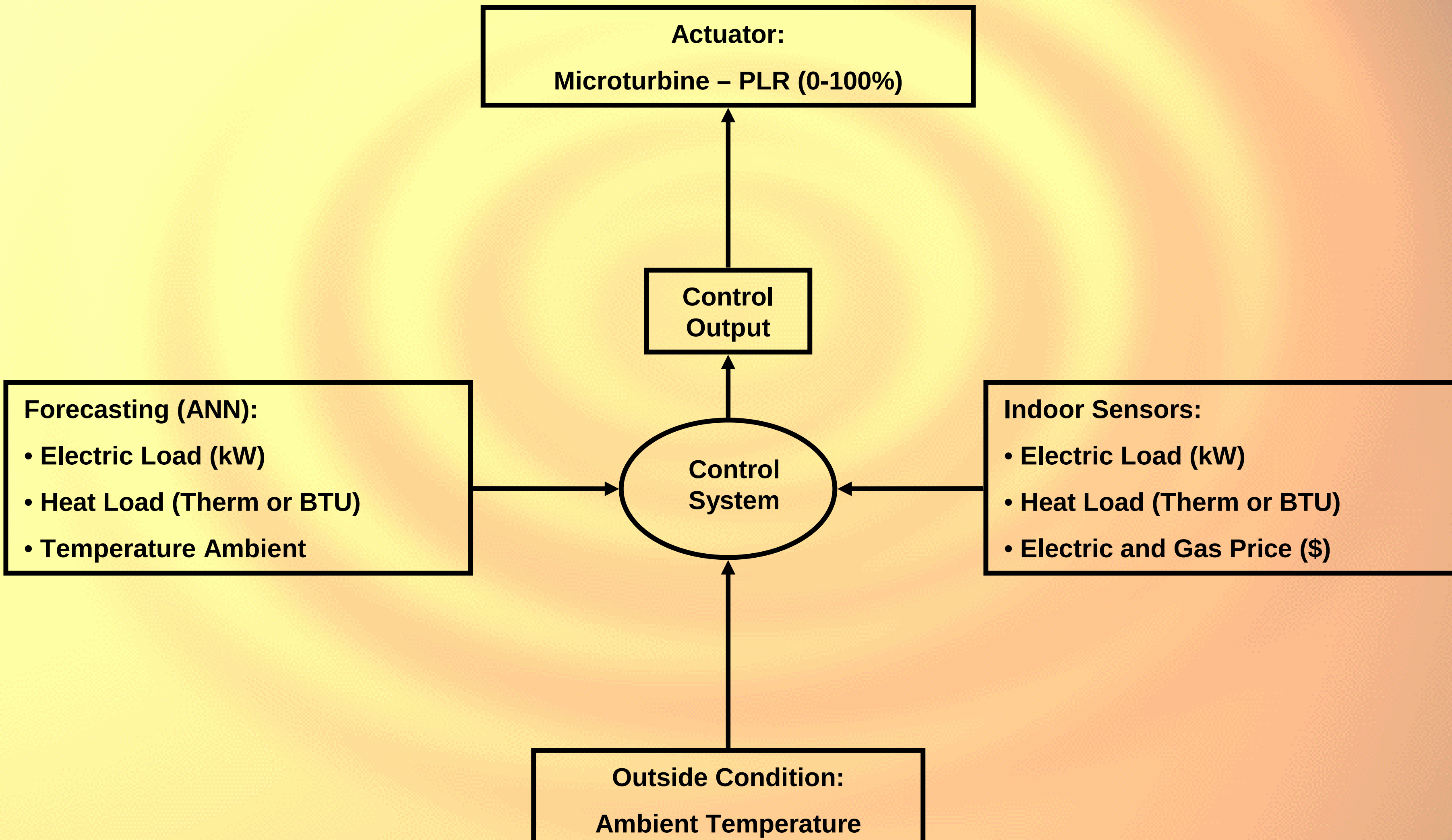
Task 7

CHP OVERALL SYSTEM Control



Task 7

Process Flow



Task 8

- DG Interconnection Structure
  - Understanding the best alternatives for connecting CHP to the existing electric power grid is essential for both the reliability of the current electric system and for CHP as an energy alternative.
    - Results
      - Report completed and submitted to NREL summarizing the various issues relating to the current status and issues regarding the interconnection of DG to the grid.
        - State and Federal regulations, standards, and issues
        - Industry standards
        - Utility practices and policies
        - Tests of interconnection interactions and influences

Task 8

- Sample Utility Survey Results
  - Over 100 utilities contacted with follow up, 16 replied
  - Standards that are included as part of local utility standard for DG interconnection

Utility	ANSI/IEEE	NEC	NESC	NFPA	UL
1	519	√	NR	NR	√
2	C37.90	240, 690	NR	NR	√
3	519, C37.90, ANSI84.1	√	√	NR	NR
4	100, 386, 519, 929, 1547, C37.108, 37.13, 37.2, 37.41, 37.90, 37.90.1, 37.90.2, 37.95, 62.41, 62.45, 62.92.1, 84.1	√	√	√	1741-2000 98-1994 363-2000 489-9
5	80	√	√	√	√
6	519, 929, C37.90, ANSI 432.2, 41.1	√	NR	NR	1741
7	80, 242, 446, 519, 1001, 1021, 1109, C37.90, 37.95	√	√	√	NR
8	√	NR	√	NR	NR
9	367, 487, 519, 929, C37.90, 37.90A, 37.90.1, 37.90.2, 37.98, 37.2, 39.1, 39.5, 57.13, 84.1, 62.41	√	√	NR	1741
10	141, 519, C37.2, 57.110, 84.1	√	√	NR	NR
11	519, 929, 1547, C37.90.1, 62.41, 62.45	100	NR	NR	1741
12	929	705	√	NR	1741
13	519	NR	NR	NR	NR
14	242, 446, 1001, 1021, C37.90, 37.95	√	√	√	NR
15	84, 519, 929, C37	701, 702, 705	NR	NR	NR
16	519, 929, C37.90, 62.41	√	√	NR	1449

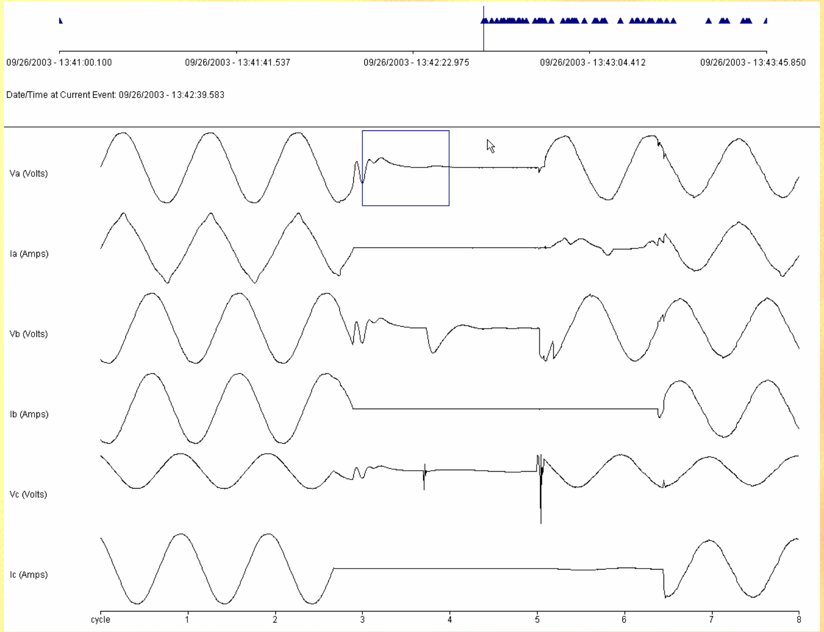
Task 8

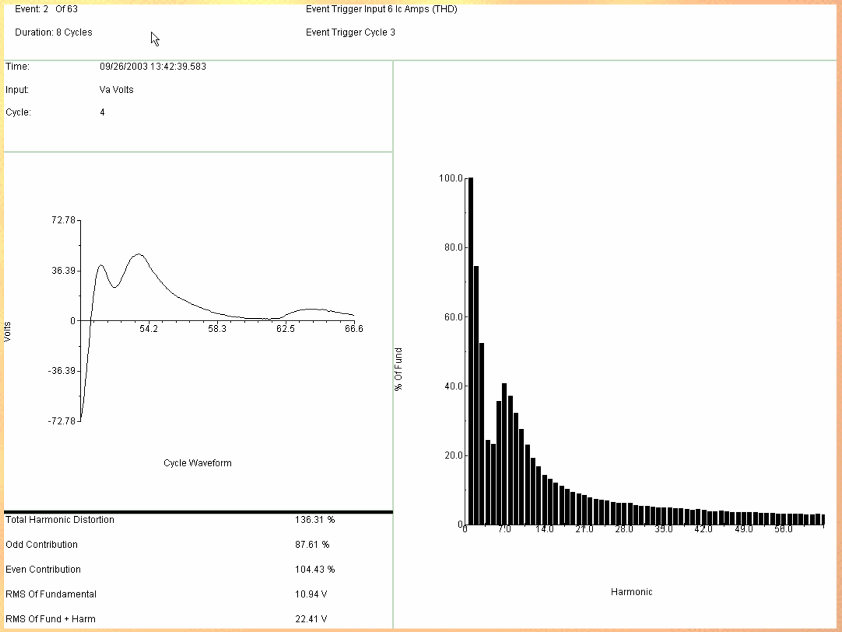
- The wave form that follows is illustrative of the types of tests that were conducted to better understand the issues regarding the interaction of DG with various power sources and the grid.
  - A commercial transfer switch was wired with the grid connected to the emergency input of the switch and a microturbine connected to the main power input. The wave form shows the operation of the transfer switch when the turbine has started and the power supply to the office building is transferred from the grid (backup) to the turbine in standalone mode (normal source).
  - Various other configurations were also considered as part of the testing.
  - In prior reports, issues relating to inductive and resistive transient response were analyzed. Design and operational recommendations were presented including applications with multiple turbines and a fly wheel.

Task 8

- In the following test all computers in the test office building in Gary tripped when the transition from the grid was made to the turbine in stand alone mode. Recommendations to deal with this situation are under development.

Commercial transfer switch transition:



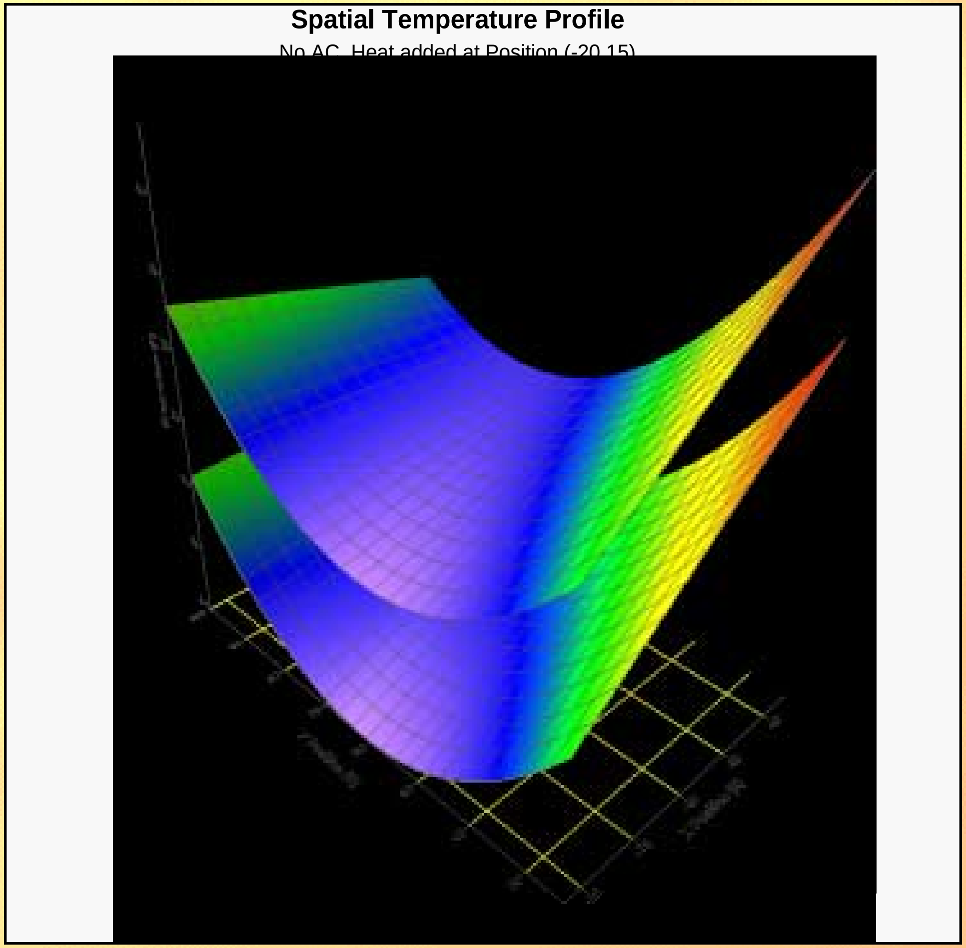


Task 9

- **CHP system integration and performance recommendations**
  - Results
    - Various CHP building integration and optimization schemes were investigated for inclusion in final report.
      - To compete with conventional sources, CHP must show an energy and quality advantage.
        - Due to the lower efficiency of many CHP electric production devices, it is important to use as much heat as possible.
        - The mix of heat using devices must be sequenced and then optimized to maximize benefit.
        - Current desiccant technology generally uses heat more efficiently than current absorption technology, reducing electric usage through displacement of air conditioning.
        - Power quality on transition to and from the grid is a difficult situation requiring special attention. Inductive transients are a major concern for inverter based generation and current designs provide minimal power quality improvement.
        - If there is to be significant future market penetration of CHP, the CHP system must become an optimized part of the total building energy system with integrated control functions.
        - Careful design consideration of equipment mission, reliability, and stability is required for application in real life operating situations.

Task 9

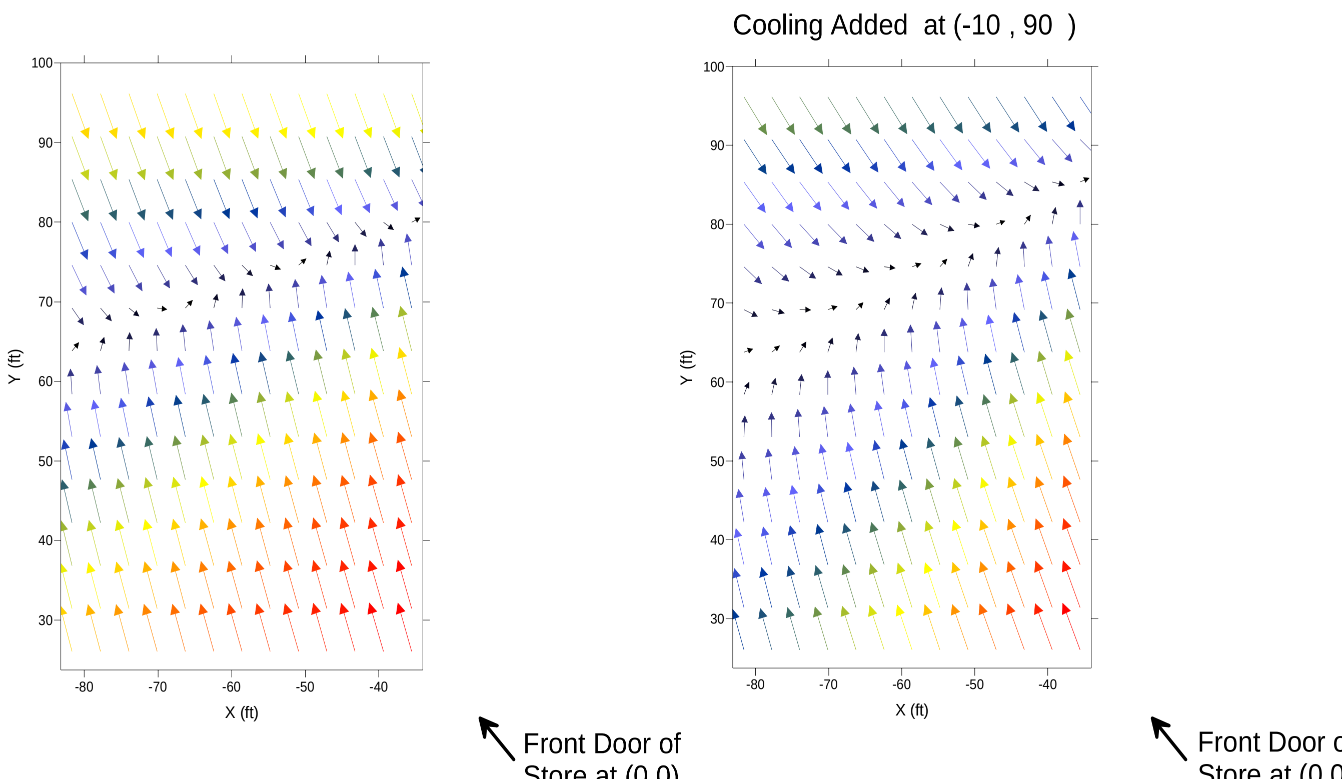
- By understanding how a building responds to changes in temperature and humidity, it is possible to develop control schemes that significantly improve energy efficiency.
  - Chesterton Drugstore Example



Task 9

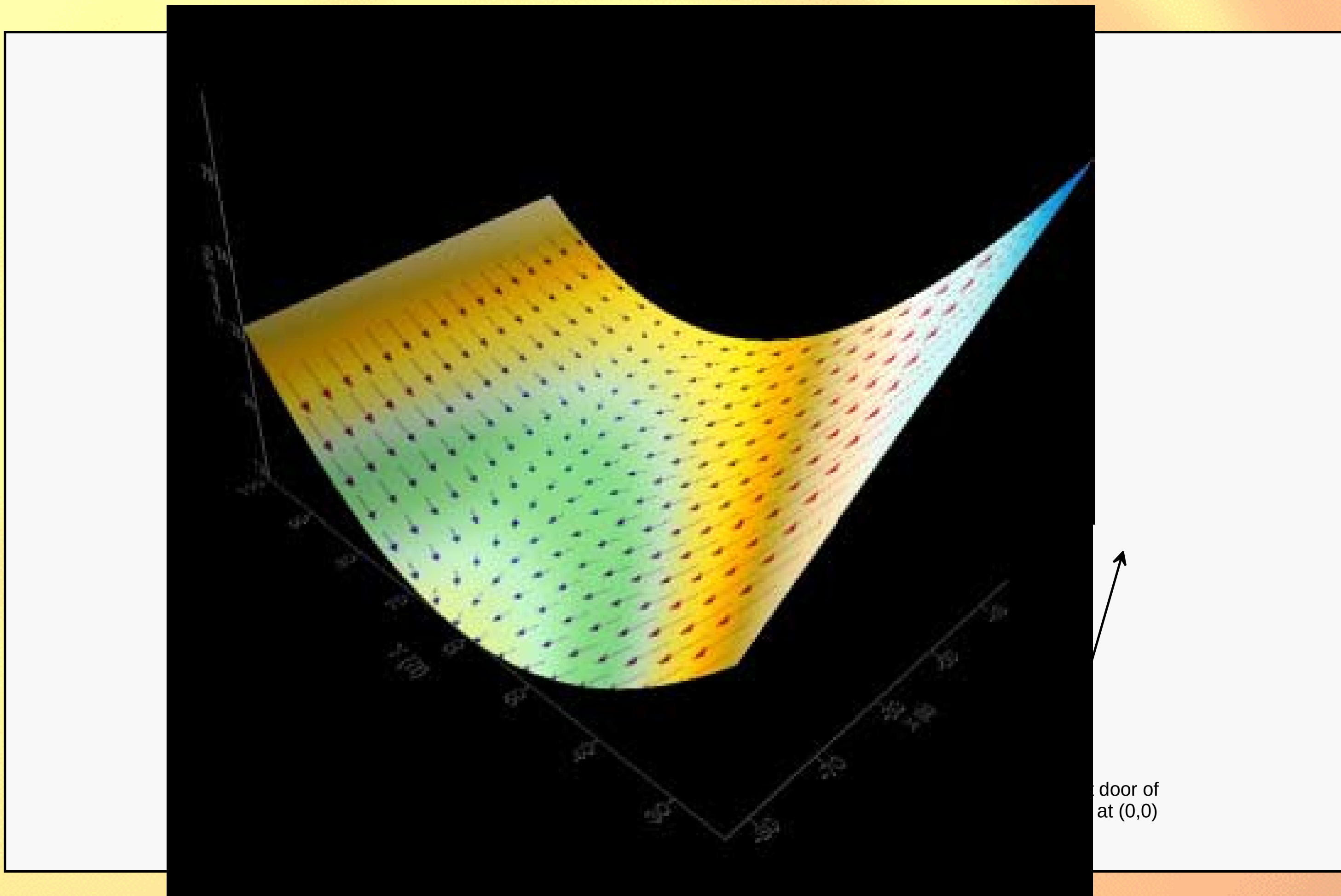
- By understanding the transient response of a building to perturbations in the energy profile it is possible to arrange for desired temperature and humidity states by making smaller and more efficient changes than are possible with conventional set point control.
  - Chesterton drug store test site temperature gradient examples

Gradient Fields for Case With Heat Introduced at (-20,15).



Task 9

- Chesterton Drug Store Temperature Gradient Vector Diagram Example
  - A library of responses to various dynamic energy changes was assembled. This is used as input to a feed forward adaptive control scheme that employs a fuzzy logic in conjunction with a neural network that learns energy usage patterns and adapts to changes in and optimizes building energy usage efficiency.

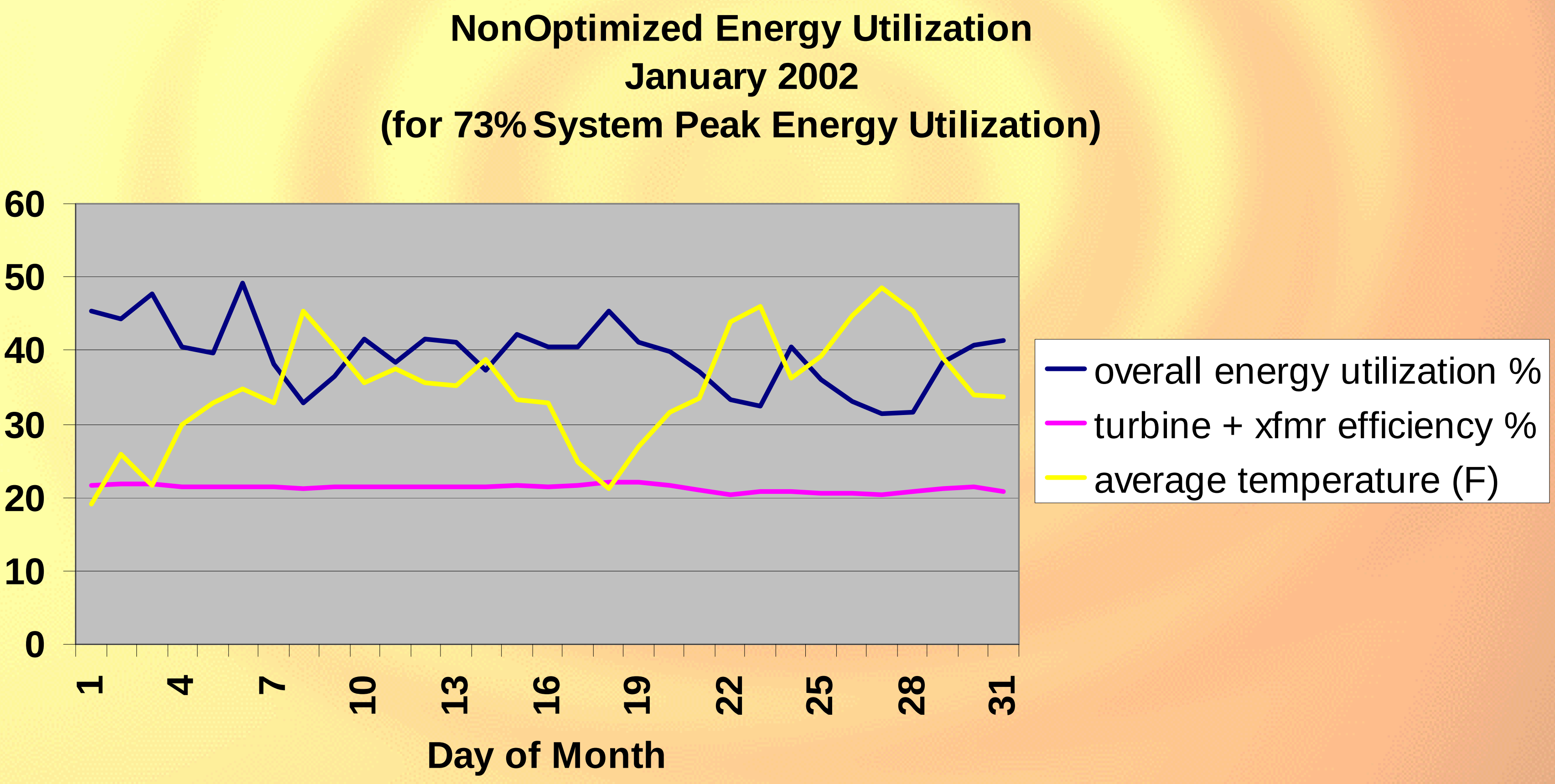


Task 9

- Optimizing the mix and operation of CHP devices
  - Quick running model written in MathCad was used for Gary test sites and was interfaced with real time data acquisition for various tests.
    - Initial model was benchmarked to small office building.
    - Model is being used to predict optimal CHP design and value for Gary site and for larger office buildings in Minneapolis, Minnesota and Miami, Florida.
    - Factorial experimental designs were used to determine the optimal mix of CHP components and operating schemes.
  - Optimizing dynamic MatLab model is being developed for Chesterton test site.
    - True dynamic model
    - Neural networks
    - Fuzzy logic

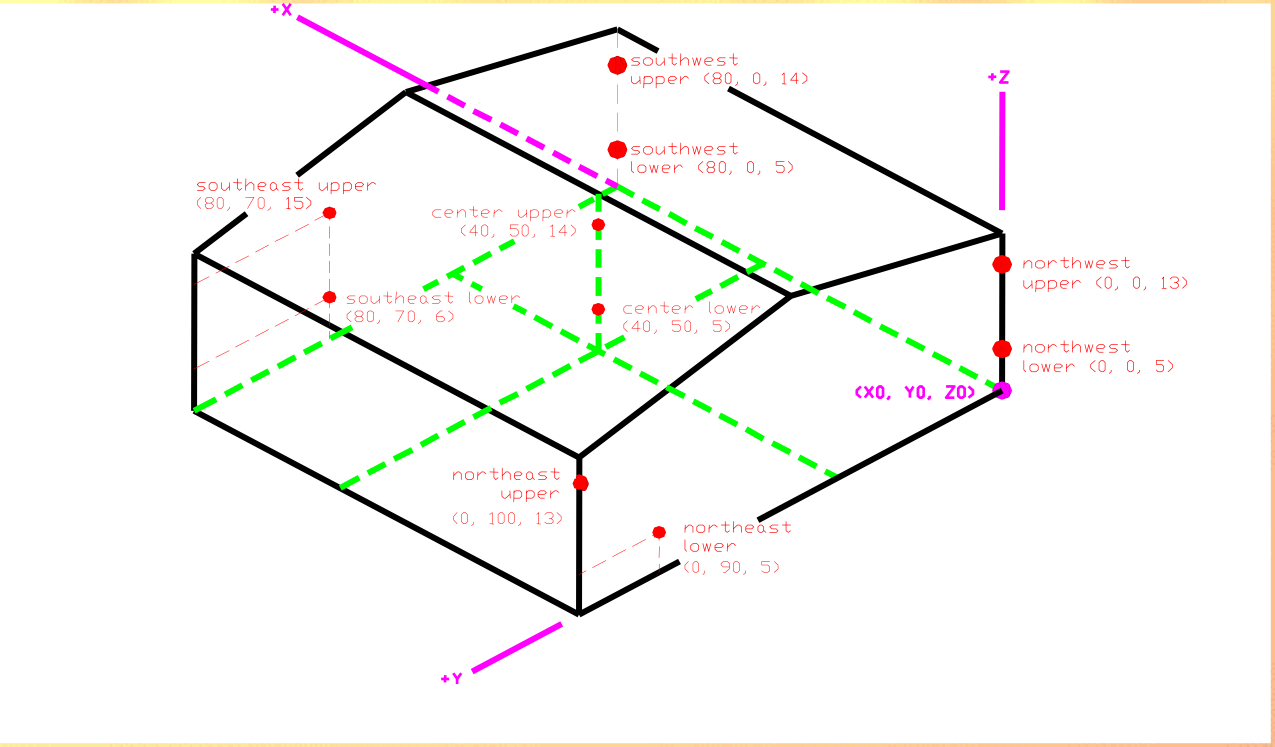
Task 9

- Chesterton drug store test site CHP energy utilization example.
  - The optimal control system will maximize the energy utilization and increase the energy utilization.



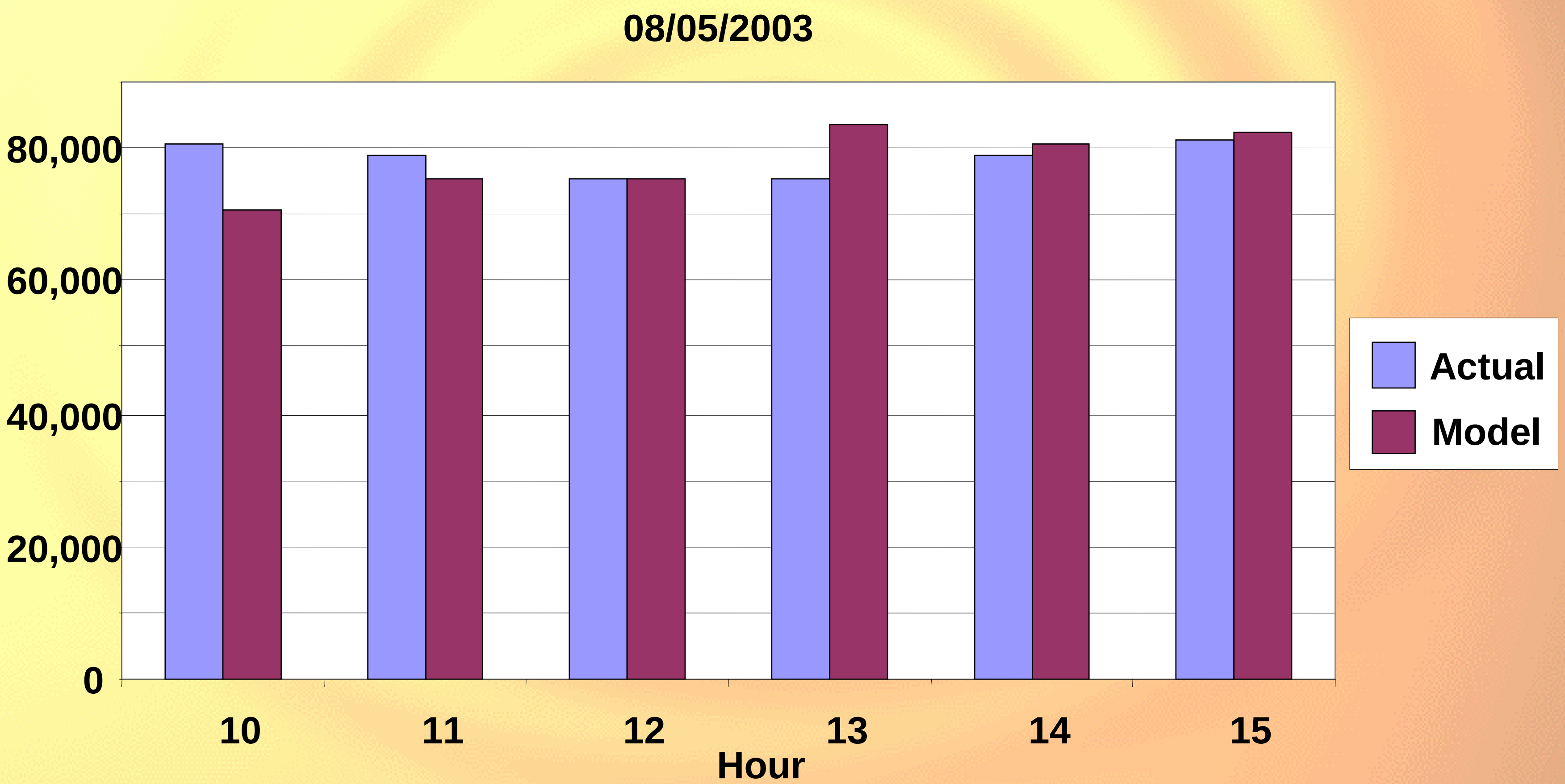
Task 9

- Gary Test Site 2 (Warehouse) Temperature and Humidity Sensor Locations for inclusion and benchmarking of building model.
  - A desiccant dehumidification system is being added to investigate how CHP technology can be used to meet energy needs and simultaneously reduce the rework required for stored steel stock resulting from corrosion caused by high humidity levels.



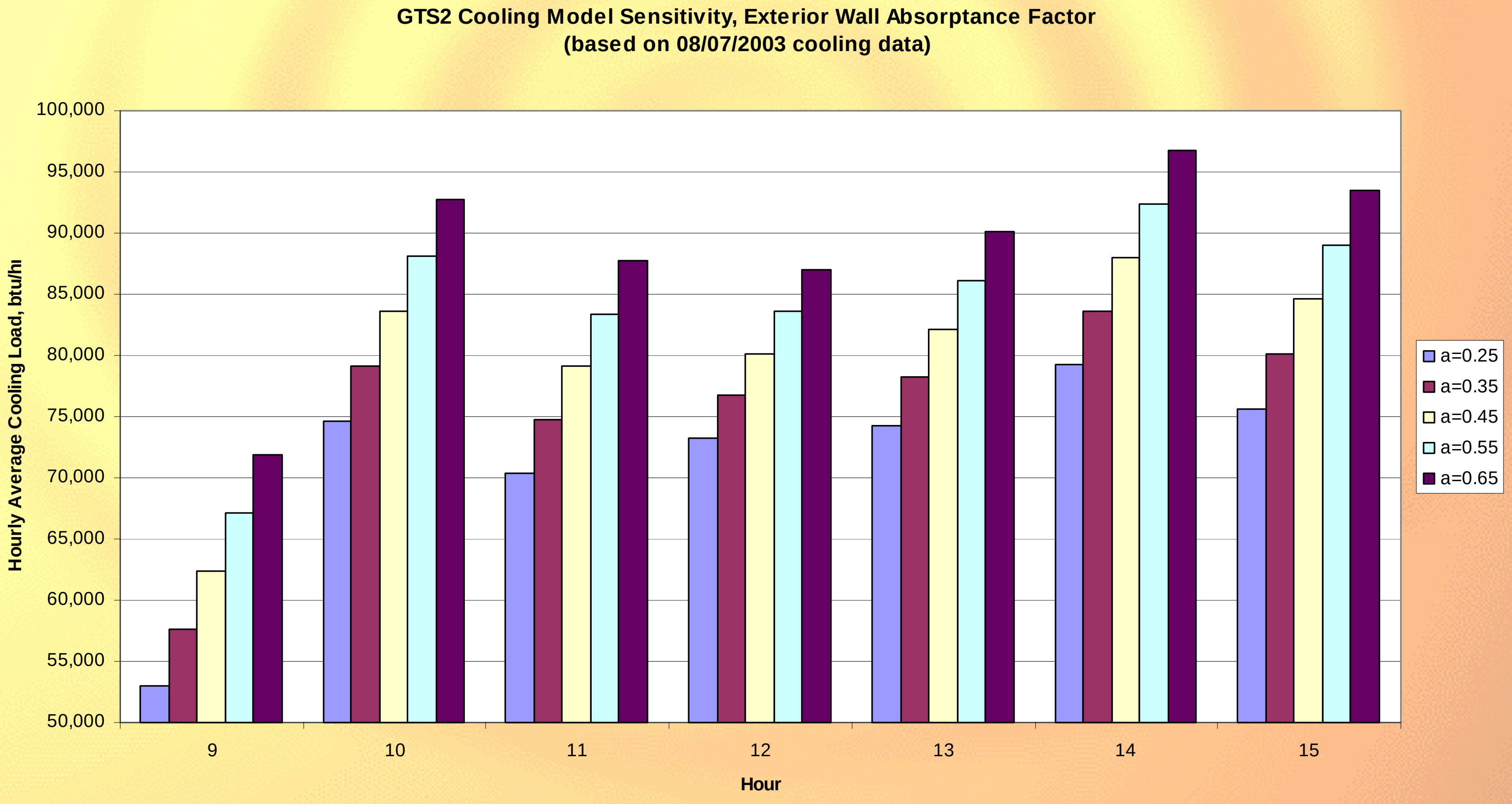
Task 9

- The building model was validated for various conditions.
  - Benchmarking example
    - Second Gary Test Facility (Warehouse) Hourly Cooling Load, btu/hr



Task 9

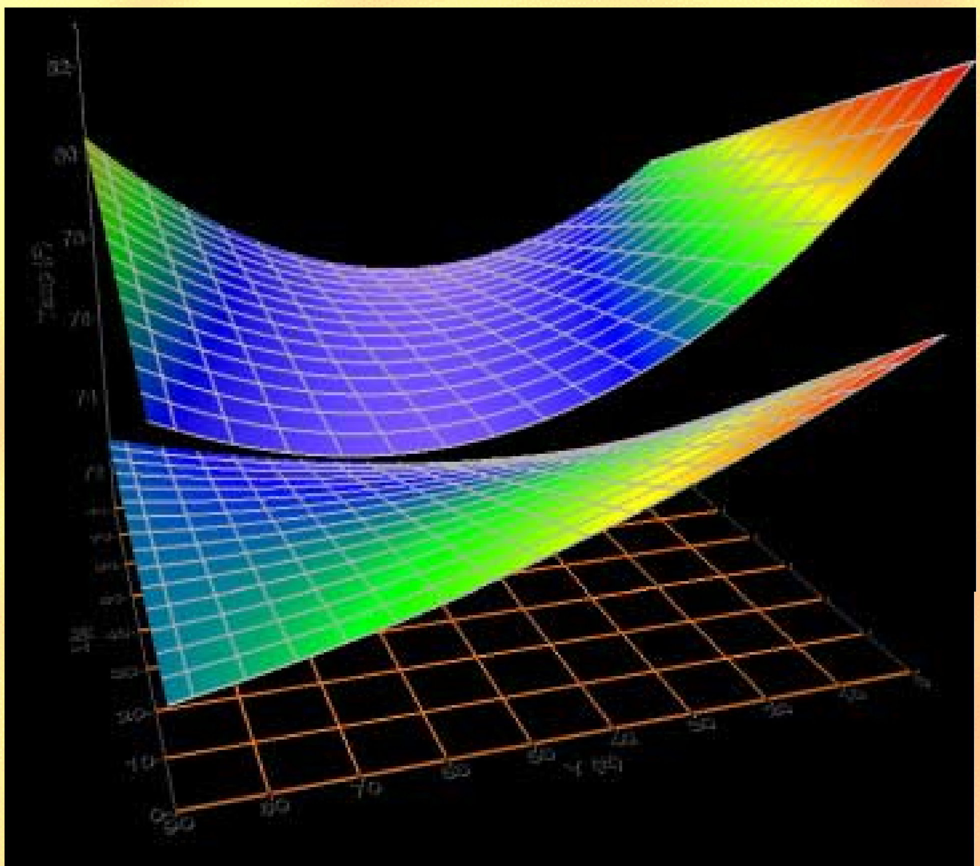
- Sensitivity studies were run and used for benchmarking of various parameters influencing the energy profile for the building model.
  - Example of sensitivity study considering influence of exterior wall absorbance on cooling load for the building.



Task 9

- Warehouse temperature profile before and after AC addition

Front half of warehouse with insulated partition separating other half
Top surface is at start
Bottom surface is after equilibrium is reached with cool air entering at (20,20) from absorber
Cool air direction is toward (80,90) 2 ft above floor level

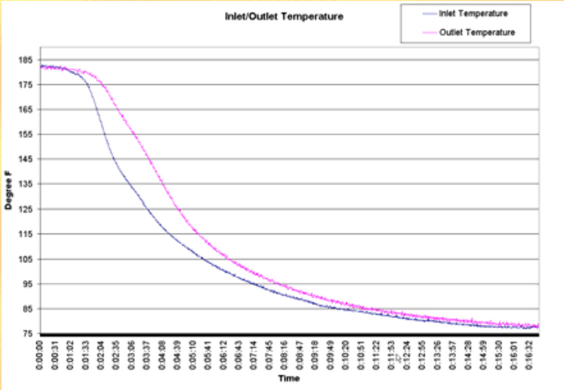


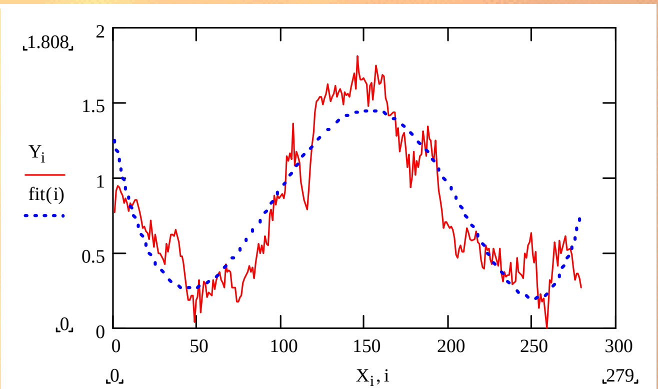
Task 9

- Building model that was developed and benchmarked for the first Gary test site is now being adapted to consider the optimal design and viability of CHP systems for use in Minneapolis, MN and Miami FL.
  - The mix of optimal CHP devices and operating schemes often heavily depends on the local environmental conditions.
    - Minneapolis system has an emphasis on electricity, heating, hot water heating, desiccant dehumidification, and energy recovery vent.
    - Miami system has an emphasis on electricity, hot water heating, desiccant dehumidification, absorption cooling.
      - Sensitivity study will consider the relative advantages of desiccant dehumidification vs absorption cooling for applications with higher humidity and temperature. An Energy Recovery Vent will be considered as one option.

Task 9

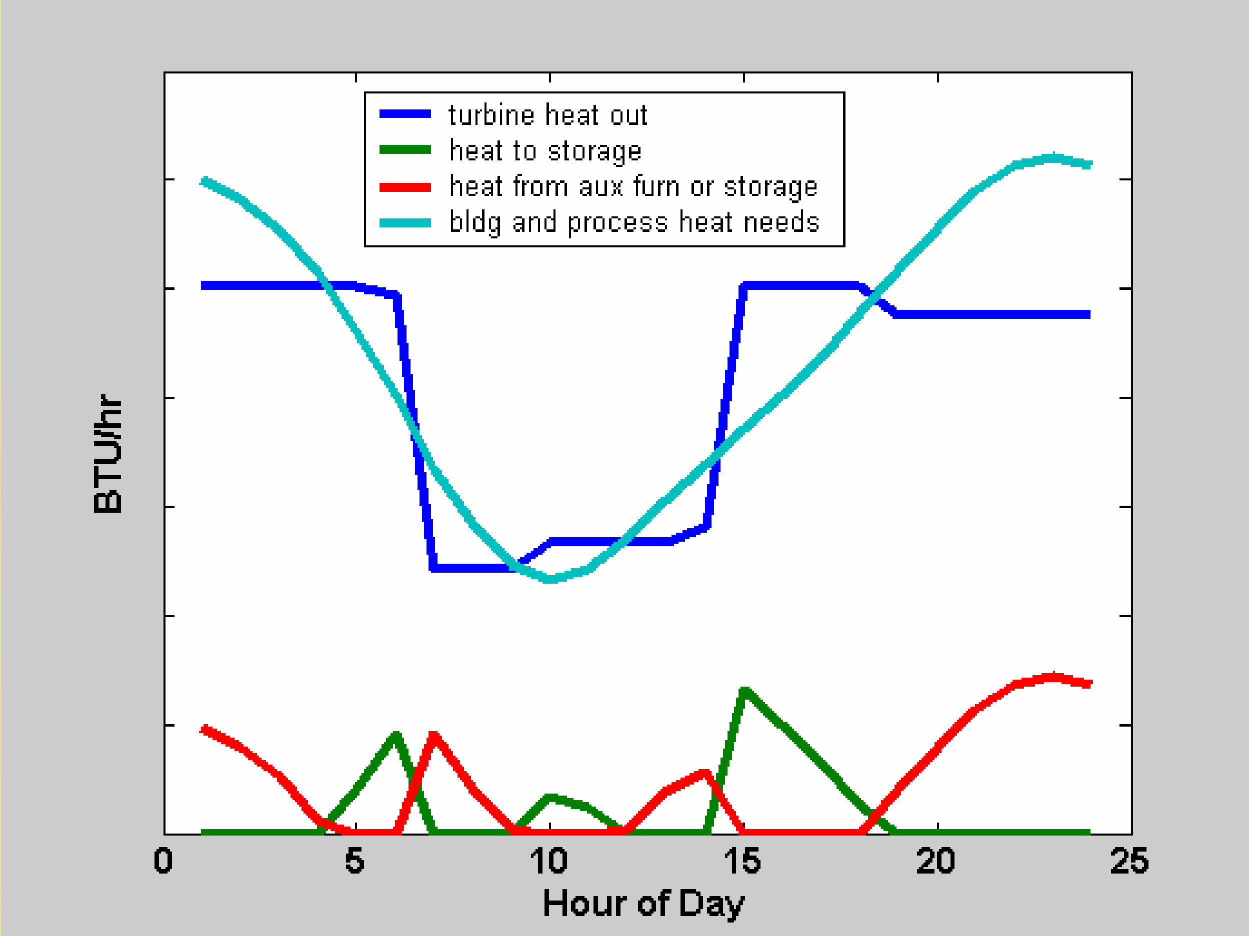
- To improve overall efficiency it is necessary to use as much heat as is possible. Heat storage can significantly improve heat utilization and hence the overall efficiency and viability of CHP.
  - In the first option year a low temperature storage system was designed, constructed, and tested using eutectic salt.
  - In the second option year a prototype high temperature fast response unit was designed, constructed, and tested.
    - High Temperature Fast Response Heat storage
      - Plastic phase change material in a fluidized bed configuration
        - Changes phase at 176 F





Task 9

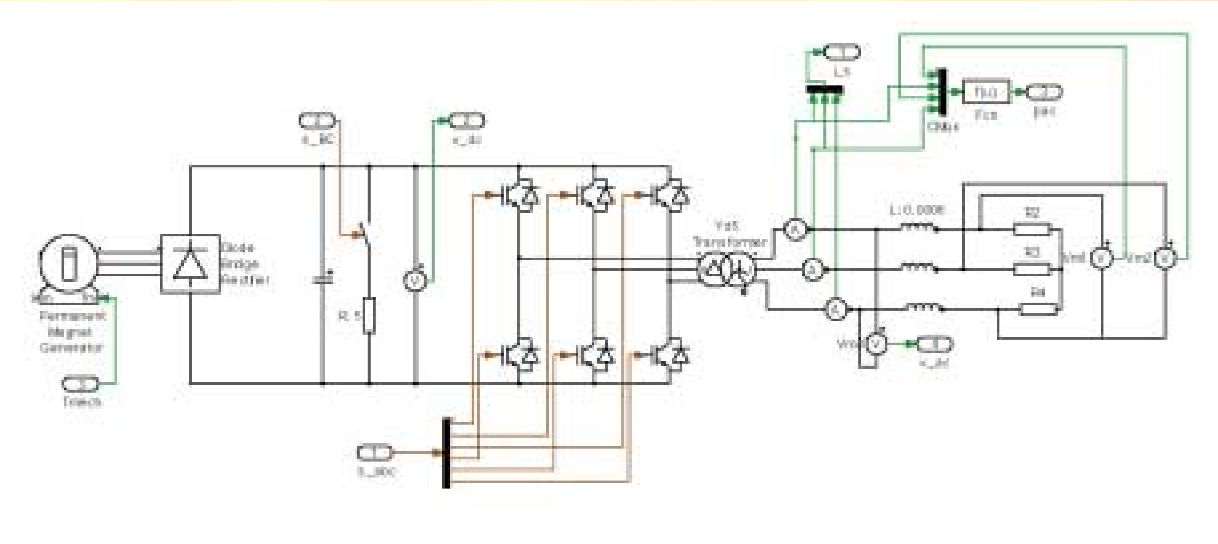
- Example of heat production and storage options for commercial business in IN



Task 10

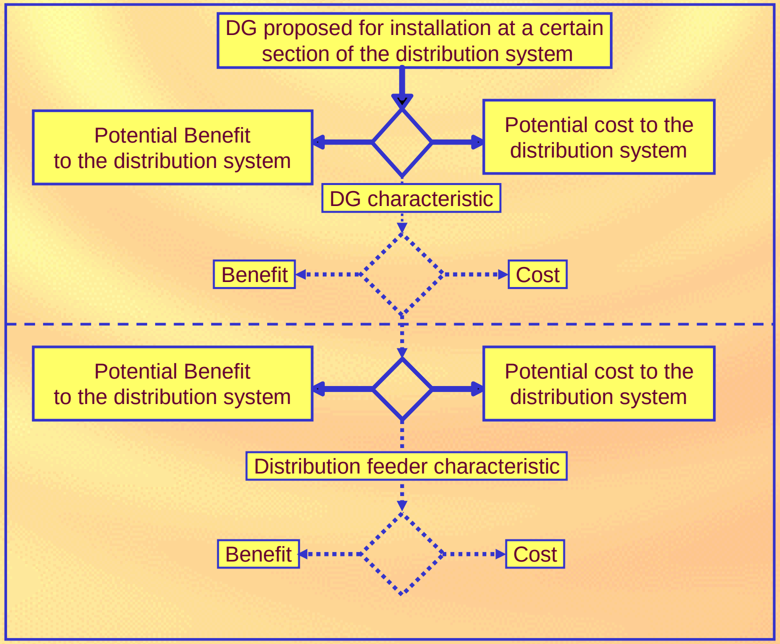
- Controllable Inverter model for DG that improves power quality
  - Results
    - Currently developing and testing model
      - Basic goal is to develop a model for an inverter for use in DG devices that is state of the art and improves local power quality.
      - Sub contractor: Chee-Mun Ong, Electric and Computer Engineering, Purdue University, Lafayette, IN

Initial Space Vector Modulation Model



Economic benefit of DG to electric distribution

- Results
  - Currently developing concepts for economic and regulatory consideration of DG
    - Goal is to consider the economic and regulatory issues that may arise as the penetration of DG on electric distribution systems significantly increases in the future.
    - Sub contractor: F.T. Sparrow, Director State Utility Forecasting Group, Purdue University, Lafayette, IN



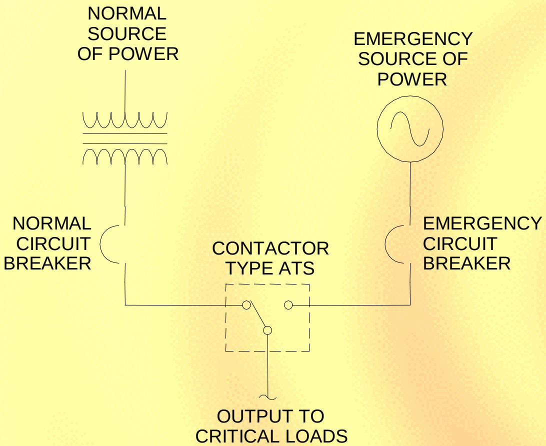
Task 12

- Electric transfer switch design issues
  - A transfer switch changes the source of power for a local load generally from parallel operation with the grid to an isolated mode on loss of grid power. It is generally essential in efforts to improve reliability of electric supply through CHP.
    - Currently the majority of transfer switches are designed for standby generator functions.
  - The purpose of this task is to determine the current state of the art of commercial transfer switches and to assess the requirements for the various available technologies.
    - A prototype transfer switch will be constructed and tested emphasizing cost and functional efficiency.
    - Subcontractor: Advanced Power Technologies, Lafayette, IN

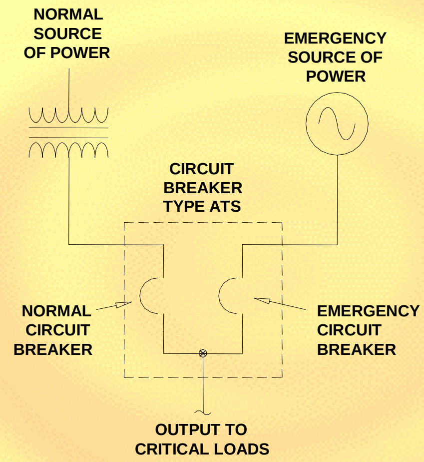
Task 12

- Common types of transfer switches were considered prior to considering alternatives.

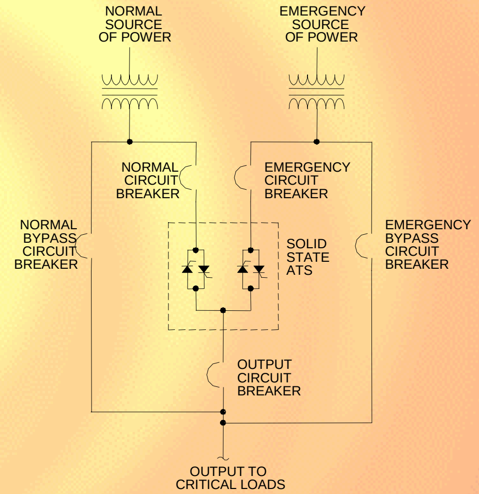
Contactor



Circuit Breaker



Solid State



ATS rating, Amps	Contactor based	CircuitBreaker based	Solid state
200	$1,800	$2,700	$29,000
400	$3,000	$3,700	$36,000
600	$4,000	$4,000	$38,000
800	$6,000	$8,000	
1200	$12,000	$12,000	
1600	$14,000	$15,000	
2000	$15,000	$16,000	
2500	$24,000	$20,000	
3000	$26,000	$26,000	

Task 13

- Explore Advanced Research Agenda for Next Generation Distribution System
  - This task involves holding a meeting with experts in electric distribution system design and operation to consider what the next generation of distribution system might look like.
  - A meeting was held in Chicago, Il on 10/9/2003 to consider the topic and a final report of the meeting is being prepared along with recommendations for future research to lead to a future distribution system.
    - Subcontractor:Resource Dynamics, Vienna, Virginia

Task 14

- Consideration of Multiple DG Units on the Distribution Network
  - The purpose of this task is to define how various DG's interact with the electric distribution network in order to determine effects for the next generation distribution network.
    - An integrated model will be developed including distribution system, distributed generation, and substations for a portion of the distribution network containing two DG installations located in Chesterton Indiana.
      - The dynamic and steady state interactions of two microturbine installations with the local utility distribution network will be considered.
  - The approach is to evaluate a range of issues, including the stability and interaction of DERs with various loads and system components.
  - The overall result will be a documented prototype model of how the modeled DGs affect the distribution network, including application notes, test plans and results of the testing including sensitivity analysis and identification of key parameters, as well as an assessment of the economic benefits derived from an integrated energy system.
  - Subcontractor: A. P. Meliopoulos, Patterson & Dewar Engineers Inc., Atlanta, GA

Life-Cycle Project Timeline

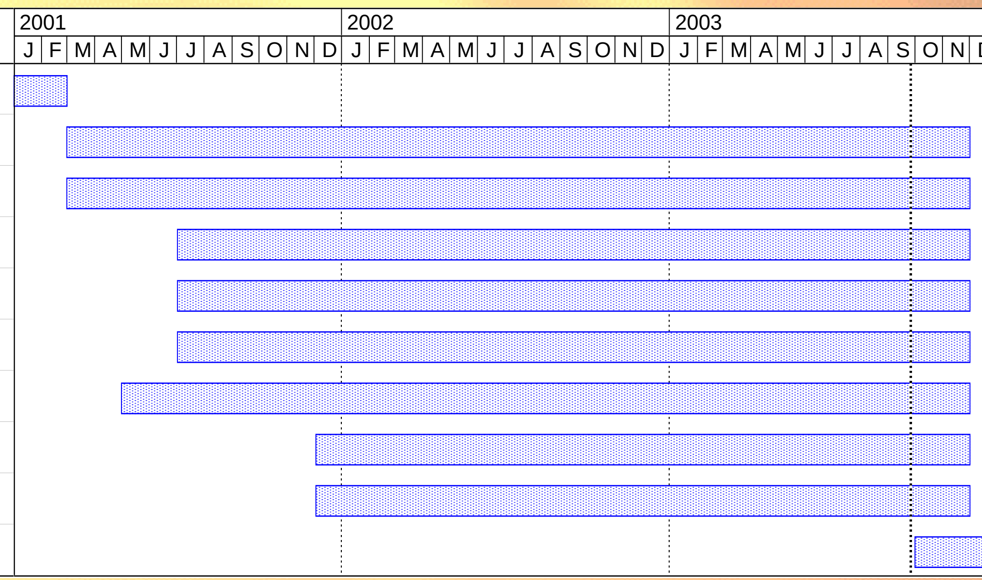
- Milestones/Deliverables
  - Monthly Reports
  - First Year Report NREL/SR-560-34966
  - Second Year Report NREL/SR-560-35054
  - Final Report – 12/31/04

- Budgets

	Total ($K)	DOE/NREL	Subcontractor
Base Year (1/2001-1/2002)	819	450	369
Option Year 1 (1/2002-1/2003)	1256	682	574
Option Year 2 (1/2003-1/2004)	1600	1150	450
Total	3675	2282	1393

Life-Cycle Project Timeline

Activity	Start	Finish
Project Scope Definition	Mon 1/1/01	Thu 3/1/01
Micro Turbine Testing	Thu 3/1/01	Mon 12/1/03
System Controls	Thu 3/1/01	Mon 12/1/03
System Integration	Mon 7/2/01	Mon 12/1/03
Building Interface	Mon 7/2/01	Mon 12/1/03
Advanced System Controls	Mon 7/2/01	Mon 12/1/03
System Optimization	Tue 5/1/01	Mon 12/1/03
Building Integration	Mon 12/3/01	Mon 12/1/03
Integrated Testing	Mon 12/3/01	Mon 12/1/03
Final Report	Wed 10/1/03	Wed 12/31/03



Milestones are monthly reports, yearly report, progress presentations, control report, and report on codes

Life-Cycle Project Timeline

Task #	Description	Year	Status
1	**DG interconnection issues**	**2001**	**complete**
2	**Zoning and Permitting issues for DG**	**2001**	**complete**
3	**DG system integration and performance considerations**	**2001**	**complete**
4	**CHP System Design**	**2002**	**complete**
5	**DG interconnection development**	**2002**	**complete**
6	**CHP performance and interactions issues**	**2002**	**complete**
6A	**DG interconnection demonstration**	**2002**	**complete**
7	**CHP system design recommendations**	**2003**	**ending**
8	**DG interconnection structure**	**2003**	**complete**
9	**CHP system integration and performance recommendations**	**2003**	**ending**
10	**Controllable inverter model for DG**	**2003**	**ongoing**
11	**Economic benefit of DG to electric distribution grid**	**2003**	**ongoing**
12	**Electric transfer switching design issues**	**2003**	**ongoing**
13	**Explore research agenda for next generation electric distribution system**	**2003**	**ongoing**
14	**Consideration of the interaction of multiple DG units on the distribution network**	**2003**	**ongoing**

FY03 Progress and Accomplishments

- This project has developed and/or tested various processes, devices, and systems aimed at improving the technical viability and understanding of CHP technology with the intent of accelerating and widening the acceptance of CHP as a nationally important energy source and managing loads to improve overall electric distribution performance and value.
  - Conducted a three-phase research and development effort to advance distributed power development, deployment, and integration.
  - Developed, tested, and optimized (electric/natural gas/ renewable energy) distributed power systems in Gary and Chesterton, IN
  - Developed and conducted laboratory and field tests of methodologies and advanced control systems (including command, communications, monitoring, efficiency, and energy system operation)
  - Fully documented results. At conclusion, will provided DOE with computer data base of relevant information along with final report.

FY03 Progress and Accomplishments

- Task Description and Status
  - Details of the tasks for the base year and option year 1 can be found in the yearly reports published by NREL (NREL/SR-560-34966, NREL/SR-560-35054)

Task #	Description	Year	Status
1	DG interconnection issues	base	complete
2	Zoning and Permitting issues for DG	base	complete
3	DG system integration and performance considerations	base	complete
4	CHP System Design	Option 1	complete
5	DG interconnection development	Option 1	complete
6	CHP performance and interactions issues	Option 1	complete
6A	DG interconnection demonstration	Option 1	complete
7	CHP system design recommendations	Option 2	ending
8	DG interconnection structure	Option 2	complete
9	CHP system integration and performance recommendations	Option 2	ending
10	Controllable inverter model for DG	Option 2	ongoing
11	Economic benefit of DG to electric distribution grid	Option 2	ongoing
12	Electric transfer switching design issues	Option 2	ongoing
13	Explore research agenda for next generation electric distribution system	Option 2	ongoing
14	Consideration of the interaction of multiple DG units on the distribution network	Option 2	ongoing

Impacts and Benefits

- Combined heat and power holds the promise to be an important part of the energy supply mix of the future.
  - Various aspects of power quality, electric supply reliability, and compatibility with the existing electric grid have been investigated in real life commercial applications as well as in the laboratory.
    - This has resulted in recommendations for Improvements to CHP technology.
    - Reduction of power quality and reliability issues for the CHP system and enhancements of the understanding of the operational interface to the grid thereby leading to cost savings and improved reliability.
  - Advanced control schemes employing dynamic control technology have been developed that increase the value of CHP systems by integrating the CHP system into the building design as well as its energy control scheme.
    - Based upon experience from field tests of CHP systems that started approximately 6 years ago, this project has attempted to provide answers to a variety of technical and policy issues hindering wide spread implementation of CHP.
    - This work has produced recommendations for optimizing CHP designs that increase the SPARK spread and hence increase the fraction of projects that are technically and economically viable for use of CHP.
    - The understanding of how various CHP components behave individually as well together in actual commercial applications has been increased. Recommendations for optimizing CHP system designs were made.

Interactions & Collaborations

- **NREL**
  H. Thomas
  - **NET**
    R. Kramer
    - **Energy System**
      NET:
      R. Kramer
      R. Sichtermann
      J. Richards
      J. Moehl
    - **Control Systems**
      NET:
      R. Kramer
      DU: R. Shoureshi
    - **Testing and Prototypes**
      NET:
      R. Kramer
      J. Richards
      J. Moehl
      Contractor
    - **Building Interface and Renewable Interface**
      NET:
      R. Kramer
      R. Sichtermann
      J. Moehl
    - **Tasks 10-14**
      NET:R. Kramer, R. Sichtermann,
      PU: C. Ong, T. Sparrow
      RD: E.Hunt
      P&D: A. Meliopoulos
      APT: A. Steselboim

NREL = National Energy Renewable Laboratory, NET = NiSource Energy Technologies,
DU = Denver University, PU = Purdue University, RD = Resource Dynamics,
P&D = Patterson & Dewar Engineers, APT = Advanced Power Technologies

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